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Original Article

Technical and Economic Improvement of Soil-Lime in Subfloors for Rural Constructions

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Abstract - *The aim of the research is to assess the technical and economic viability of lime-stabilized soil in creating sub-floor layers for rural homes in the Chilca district, located in Junín (Peru). The study focuses on a geographic area characterized by a high degree of dilapidation due to poverty among families that live there; therefore, it considers the construction of poorly-built houses that lack finishing materials for walls and floors. To establish the technical characteristics of the soil, the author used Modified Proctor Test, unconfined compressive strength and durability tests. The tested lime content included 0%, 4%, 6%, 8% and 10%. A lime content of 6% was found to give the most favourable results when used in a sub-floor layer application while meeting the strength and durability criteria with less lime than that used at other higher levels of addition. A unit price analysis was performed to evaluate the economic feasibility of the subfloor layer constructed with lime-treated soil. This analysis used the unit of an area of 1 m². According to the quantitative analysis findings, the lime-based alternative has an approximate 47.23% less cost than the standard concrete system. Furthermore, lime-based construction has a straightforward installation process, which makes it a practical and viable choice. Using a lime- based product may also limit the use of materials purchased from outside sources because the method encourages using as many locally sourced materials from the area as possible, with the exception of lime, which is the only material added from an outside source*.

Keywords - *Cost, Dosage, Durability, Strength, Subfloor layer, Soil-Lime.*

1. Introduction and Background

Historically, soil has been one of Peru's central building materials for people. While, as a basic form of construction material, soil has lost some of its significance over time, it remains of major historical and technical significance to Peruvians [1]. The pre-Hispanic cultures that existed in Peru successfully developed watertight rammed earth (tapial) and quincha (woven cane) methods of construction that are still employed today throughout many regions of the country, with adobe buildings representing upwards of 27.91% of all rural housing units. The continued use of these material-based systems suggests that traditional construction technologies continue to provide significant contributions to the culture of construction in Peru and demonstrate economic limitations on housing in rural Peru [2]. However, many of these buildings are currently built and inhabited in precarious conditions [3], often lacking plaster and basic finishes that ensure durability and healthy living conditions so this situation is exacerbated when considering data from the 2017 National Census, which reports earthen floors in 2,448,766 dwellings [4], a condition that evidences the absence of basic comfort for their inhabitants and reflects structural inequalities in quality of life, also added to these problems are the lack of adequate technical regulations and limited knowledge of improved construction techniques [5], which has led to high-risk habitability conditions, especially in seismic areas such as the Peruvian coast and highlands. As an aggravating factor, the rise in construction material prices, which recorded an increase of 9.1% [6], constitutes an additional obstacle to improving existing homes and building new housing solutions that ensure decent conditions for rural families. In response to this problem, this work proposes the implementation of an economical, efficient material with easy access and practical application, composed of a dosed mixture of earth and lime. Applied as a subfloor layer, this system seeks to significantly improve habitability conditions in rural houses. Since Junín has the capacity to produce more than 600 tons per day of lime [7] at a low selling cost, Peruvian regulations [8] governing the use of earth–lime combinations in road applications highlight the properties of this material, indicating that it is easily workable and ideal for resisting compressive and tensile stresses.

Lime is often added to fine-grained soils to improve their behavior. In clayey soils, the first changes happen soon after mixing, mainly due to cation exchange and flocculation-agglomeration. As a result, the soil becomes less plastic and easier to work with. As time passes, lime reacts with the silica and alumina already present in the soil. This reaction forms cement-like compounds, which improve the soul's strength, stiffness, and durability. Many prior studies have demonstrated increased compaction characteristics, compressive strength, and improved resistance against environmental degradation of materials that are naturally or sustainably derived from lime stabilization. For this reason, lime stabilization is seen as a sustainable and economical option in construction, and it has been commonly applied in transportation infrastructure projects; there also exists an increasing interest in using this same method for the construction of low-income housing systems.

The study by Saing et al. [9] in Indonesia is particularly relevant among the reviewed studies because the focus of this study was to improve the carrying ability of lateritic soil for roadway construction through lime stabilization. In their research, Saing et al. used lime content in amounts of 3%, 5%, 7%, and 10%, the mixes were prepared using the soil's maximum dry density as a reference. After 28 days of curing, the 10% lime mixture performed better, with almost three times more strength and load-carrying capacity than the unstabilized soil.

Dhar and Hussain [10] studied how lime stabilization could improve the strength and bearing capacity of subgrade soils, in addition in their experimental program, in that study, the samples were treated with 3%, 5%, 7%, and 9% lime and cured for 0, 4, 14, and 28 days. The authors found that lime increased the soil strength, and the improvement became more evident with longer curing. With only 3% lime, the compressive strength reached 345 kPa after curing, which meets the established requirements for the California Bearing Ratio (CBR) of lime-treated soils intended for subgrades in low-traffic rural roads.

The study developed by Rodríguez and Hidalgo [11] focused on analyzing the behavior of residual soils stabilized with lime, evaluating different proportions of this stabilizer and variations in the material gradation, in addition in their methodology, the authors examined mixtures with lime contents of 3%, 6%, 9%, and 12%. In that work, lime was combined with soils at fine/coarse proportions ranging from 0%/100% to 50%/50%. The strength tests showed that the most effective lime content was between 6% and 9%, since this range improved the soil bearing capacity more noticeably, evidenced by the CBR (California Bearing Ratio) test, which recorded an increase of up to 200% in the support capacity of the stabilized material.

Additionally, reference is made to the study conducted in Peru by Barraza [12], which this research, 2.25% lime was added to clay soil to see how it affected its behavior. The results showed changes in the California Bearing Ratio test. Specifically, reductions in the plasticity index of 9.42%, 8.87%, and 10.95% were observed in three different samples, along with notable increases in CBR values of 266.67%, 283.33%, and 248.48%, respectively. These results suggest that lime has good potential for soil stabilization and lowers soil plasticity.

In line with previous research, more recent research by Khayat et al. [13] has further analyzed the physicochemical mechanisms that explain the improvement of soils stabilized with lime. Specifically, it has been shown that the incorporation of lime into clay soils not only modifies their mechanical properties but also their chemical behavior and microstructure through pozzolanic activity. In this process, the calcium provided by the stabilizer reacts with the siliceous and aluminous components of the soil, generating cementing products such as Calcium Silicate Hydrates (C-S-H) and Calcium Aluminate Hydrates (C-A-H), which contribute to reducing plasticity, increasing strength, and decreasing expansivity, effects that develop progressively over curing time.

Even though previous research has shown that lime treatment can enhance the mechanical performance of soils used in pavement layers and road subgrades, limited research has evaluated its potential as a subfloor material for rural housing, particularly under the socioeconomic and construction conditions found in developing regions and most previous investigations have focused primarily on strength improvement, bearing capacity, or pavement performance, while the combined assessment of technical performance, durability, and economic feasibility for housing applications remains insufficiently explored, because there is a lack of studies addressing the use of locally available soil-lime mixtures as a low-cost alternative to conventional concrete subfloors in vulnerable rural communities of Perú, this knowledge gap limits the implementation of affordable and sustainable flooring solutions capable of improving housing conditions in low-income populations.

Based in this gap, this study examines the technical and economic viability of using soil stabilized with lime as a subfloor material for rural houses in Cerro San Cristóbal, Chilca District, Peru because lime contents of 4%, 6%, 8% and 10% were analyzed through Modified Proctor, unconfined compressive strength, and durability tests, complemented by a unit price analysis and the objective was to identify the optimum lime dosage capable of providing adequate technical performance while maintaining a low construction cost and unlike previous studies that focused mainly on transportation infrastructure applications, this research extends the use of lime stabilization to rural housing and integrates technical, durability and economic assessments within a single evaluation framework.

2. Materials and Methods

To evaluate the soil-lime subfloor system from a technical and economic point of view, the study focused on the hamlet of Cerro San Cristóbal, in the district of Chilca, Junín Department, Peru, was selected as the study area. This choice is supported by the findings of study [14], which examine self-construction practices and identify a predominance of informally built housing characterized by the absence of technical supervision and the use of inadequate construction materials. Ultimately, the deployment of this technology aspires to contribute to a major increase in the quality of life of its people.

2.1. Materials

2.1.1. Soil

Soils suitable for construction are found in subsurface strata free of organic matter [15]. In principle, any type of soil can be considered suitable for use as a construction material, since its mechanical properties can be significantly improved through lime stabilization [16]. However, soils that can be improved with a minimal amount of lime must meet certain characteristics, such as a fines content greater than 35% [16], a plasticity limit greater than 30%, and a plasticity index greater than 10% [17]. In this way, it is ensured that the soil has the reactivity and composition necessary for an effective reaction with lime.

Sample extraction was carried out manually using tools such as picks, shovels, and airtight bags, in order to characterize their properties in the laboratory and prepare them for use in the subfloor layer. To characterize the soil, sieve analysis was performed according to ASTM D-422 [18], and the Atterberg limits were determined following ASTM D4319 [19]. With these results, the soil classification was established.

Table 1. Soil particle-size distribution

SOIL GRAIN-SIZE DISTRIBUTION BY SIEVE ANALYSIS		
SIEVE	**OPENING (cm)**	**% PASSING**
3"	7.5	100.00%
2"	5	100.00%
1 1/2"	3.75	100.00%
1"	2.5	100.00%
3/4"	1.9	100.00%
1/2"	1.25	98.88%
3/8"	0.95	89.22%
N°4	0.475	85.14%
N°8	0.236	82.02%
N°16	0.118	77.00%
N°30	0.06	70.96%
N°50	0.03	63.74%
N°100	0.015	55.42%
N°200	0.0075	43.76%

The grain size analysis results obtained from all the samples collected from across the site are shown in Table 1. The values indicate the percentage of soil particles that passed through each sieve. From these results, the grain-size distribution curve was prepared, as shown in Figure 1. This curve shows that the studied soil is mostly made up of fine and sandy material, with only a lower amount of gravel.

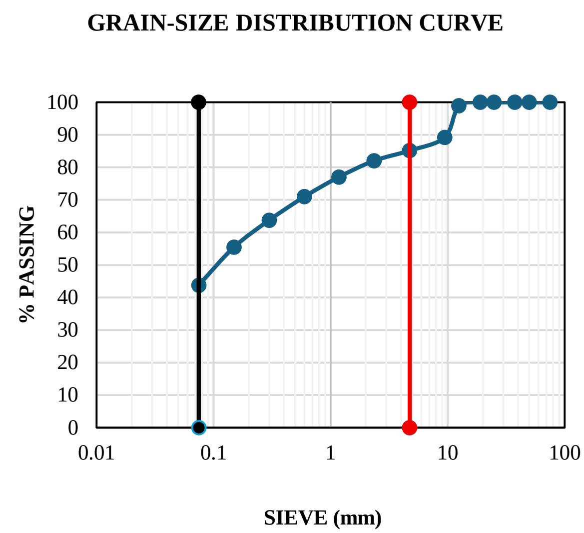

Fig. 1 Particle size distribution curve

According to the AASHTO [20] and SUCS [21] methodologies, the samples are categorized as low-quality, mostly clayey soil, as indicated in Tables 2 and 3. This outcome is in line with the prevalence of clay soils in the Cerro San Cristóbal region.

Table 2. Soil classification according to AASHTO

AASHTO CLASSIFICATION	
CLASSIFICATION	A-6(4)
MATERIAL TYPE	Clay soil
GENERAL CLASSIFICATION:	Poor to fair

Table 3. Soil classification according to SUCS

SUCS CLASSIFICATION	
% MATERIAL PASSING THE No. 200 SIEVE	43.76%
LIQUID LIMIT	36%
CLASSIFICATION	CL
MATERIAL TYPE	Fine-grained soil
CLASSIFICATION NAME	Low- to medium-plasticity clay

As demonstrated in Table 4, which aggregates the findings of the Atterberg limits tests (ASTM D4318) [19], the investigated sample displays a plasticity index of 12%. This number is in the medium-plasticity range, which describes the material as clayey soils, according to reference [8].

Table 4. Soil consistency parameters

CONSISTENCY PARAMETER	RESULT
LIQUID LIMIT	36%
PLASTIC LIMIT	24%
PLASTICITY INDEX	12%

2.1.2. Lime

The limestone rocks are heated at temperatures between 880 - 900 °C (1,600 - 1,650 °F) to get industrial lime, which is mostly made up of Calcium Oxide (CaO) but may also include other minor oxides. When used in soil treatment, there are three main types available for use: quicklime, hydrated lime, or lime slurry [16]. Hydrated lime was selected for this project because of the controlled addition of hydrated lime by reacting with the moisture content of the soil, and because it comes in bags that make it easy to manipulate, transport and apply. For this research study, the following dosages (4%, 6%, 8%, 10% of total soil weight) will be used.

Table 5. Properties of commercial lime

HYDRATED LIME	
NAME	Hades Construction Lime
PACKAGING	Bag (20.0 kg)
CHEMICAL FORMULA	Ca $(OH)_2$
STANDARD	ASTM C977-18
COMPOSITION	Calcium hydroxide – Ca $(OH)_2$

The qualities of the chosen lime for usage are shown in Table 5, where they are contrasted with the minimal standards for soil stabilization set by ASTM C977-18 [22].

2.1.3. Water

Water is important in the soil–lime mixture because it helps the components blend and react properly. When hydrated lime is mixed with soil, water helps moisten and homogenize the material, allowing the chemical reactions and physical changes needed for stabilization to occur, thus having the potential to create an even distribution of the mixture [23]. To achieve this purpose, the best practice is to use water that is free of chemicals or organic matter. Additionally, sufficient moisture should be maintained on the treated mixture for a minimum period of three hours after it has been prepared to maintain the desired properties of the mixture [24].

2.2. Research Methodology

The implementation of the soil–lime mixture for the construction of subfloor layers was carried out through a manual process, considering that the intervention area corresponds to a low-income community and the main purpose of this methodology was to enable the residents themselves to replicate the technique independently, using mainly local materials and purchasing only lime as the external input so for compaction of the mixture, a hand tamper was designed and built in an artisanal manner, consisting of a wooden handle and a plain concrete base, as illustrated in Figure 2 and this tool made it possible to achieve the appropriate density of the material, thereby ensuring the durability and stability of the floor. First, some preliminary tests were performed to see how the soil-lime mixture behaved compared with the natural soil. These included the unconfined compressive strength test, durability test, and Modified Proctor test, concluding with a quantification of time and cost for the economic analysis of the present study. Figure 3 presents a schematic that encapsulates the employed technique.

After characterizing the soil, the minimum lime content that would meet standards according to ASTM D6276-19 [25] was determined. According to the results achieved, 4% was confirmed as the minimum amount of lime that would raise the soil's pH level to 12.4, which is the ideal pH level that most standards recommend as a point at which to begin modifying the physical and mechanical characteristics of the soil. In order to determine how the additional lime additions of 6%, 8%, and 10% would alter the soil's properties under different circumstances, the additional tests quantified the maximum potential of the soil's properties and produced comparable specimens to those prepared with the minimum required amount of lime. The additional tests also permitted comparison between the two types of specimens; lime dosages were grouped together according to the amounts that were added, and no random assignment technique was used in the grouping because the purpose of testing was to compare each mixture ratio according to the same laboratory procedures. Finally, for the economic analysis of the material, the productivity of a two-laborer crew was evaluated, both residents of the study area-by quantifying the compacted soil area achieved in 8 hours per day over a period of 5 consecutive days, adopted as a representative sample within a continuous measurement process, as suggested by productivity studies [26], which recommend multiple observations to ensure the reliability of the results.

Fig. 2 Handmade tamper

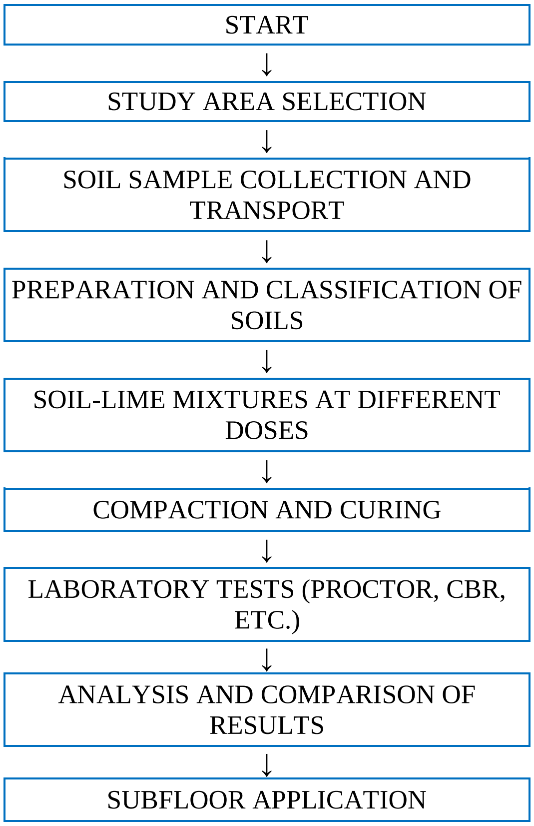

Fig. 3 Outline of the methodological process applied in the study

2.2.1. Compaction Test

This test was done to determine the optimum moisture content at which the soil reaches its maximum dry density, following ASTM D1557 [27]. A 6-inch mold, rammer, precision electronic balance, metal straightedge, and sieves of 3/4 in, 3/8 in, and No. 4 were used. The samples taken from the field were first air-dried at room temperature and then sieved to select the material for compaction. The soil was placed in the mold in five layers, applying 25 blows to each layer until the mold was filled. After compaction, the specimen mass was recorded, and a representative portion was taken to determine the moisture content by oven drying, using the weight difference before and after drying. The procedure was repeated at least five times with samples prepared at different initial moisture contents, including points on both the dry and wet sides of the curve. Once the optimum moisture content was found, the wet density was calculated with Equation (1), and the dry density was obtained with Equation (2). The wet density equation is shown below:

$$\rho m = \frac{1000(Mt - Mm)}{V} \tag{1}$$

ρm = Wet bulk density of the specimen (Mg/m³)
Mt = Combined mass of the moist specimen and model (kg)
Mm = Mass of the compaction mold(kg)
V = Volume of the compaction mold (m³)

$$\rho d = \rho m / \left(1 + \frac{w}{100}\right) \tag{2}$$

ρd= Dry density of the compacted specimen (Mg/m³)
ρm = Wet bulk density of the specimen (Mg/m³)
w = Water content (%)

2.2.2. Unconfined Compressive Strength

The test was carried out following two international standards. It included the natural soil without additive and the samples stabilized with lime, ASTM D2166-16 [28] was used, while for the lime-stabilized samples, ASTM D5102 [29] was applied so both standards cover the procedures for the preparation, curing, and testing of laboratory-compacted specimens in order to determine their unconfined compressive strength and for this study, three cylindrical molds were prepared for each of the evaluated lime contents: 0%, 4%, 6%, 8%, and 10%, resulting in a total of 30 specimens to determine compressive strength. After placing the specimen in the machine, the axial load was applied at a constant strain rate controlled between 0.5% and 2.0% per minute. The load and deformation values were recorded during the test, which allowed the stress–strain curve to be plotted for each sample. To evaluate the strength development over time, the specimens were tested after 7 and 28 days of curing. The procedure was kept the same in all cases to maintain consistency and reproducibility in the experimental program, all specimens were prepared using soil obtained from the same sampling area and homogenized after drying and sieving and during the curing period, the specimens were maintained under identical laboratory environmental conditions and protected from excessive moisture loss prior to testing, finally these procedures ensured comparable conditions among all mixtures and enhanced the reliability and repeatability of the experimental results; the specimens were identified by lime content and curing age, which allowed direct comparison of the predefined dosage levels and the unconfined compressive strength was determined using the following formula (3).

$$qu = \frac{P_{max}}{A} \tag{3}$$

qu = Unconfined compressive strength (kg/cm²)
Pmax = Maximum applied load (kg)
A = Sample area (cm²)

2.2.3. Durability

This part of the study was to see how the soil-lime mixture behaved when they were exposed several times to moisture and drying. The procedure followed ASTM D559 [30], and fifteen specimens were prepared for this test. The compacted samples were first hardened and then passed through repeated soaking and oven-drying stages. This helped to observe the loss of material, surface wear, and possible volume changes after each stage. With these results, it was possible to compare the mixtures and identify which lime percentage gave a better response under the laboratory conditions. For the test, a compaction mold of 101.60 mm diameter and 944 cm³ volume was used, together with the equipment needed for compaction and drying. Once prepared, the samples went through 12 wetting- drying cycles. Each cycle included 5 hours of wetting and 24 hours of drying. After that, the loose particles were removed with a wire brush, and the final mass was used to calculate the percentage of material loss using Equation (4).

$$Pm = \frac{M_i - M_f}{M_i} \times 100 \tag{4}$$

Pm = Loss of mass (%)
Mi = Initial dry mass (kg)
Mf = Final dry mass after 12 cycles (kg)

2.2.4. Unit Price Analysis

The economic analysis of the soil–lime mixture for subfloor layers was carried out following the methodology established in the manual Analysis of the Unit Price [31] and the process focused first on the preparation of the mixture produced in situ, considering the costs associated with labor, materials, and the tools used, then the application stage of the mixture as a subfloor layer was analyzed and for labor calculation, the criterion of a crew composed of two laborers was adopted, in accordance with the recommendation of the Peruvian Cost Magazine [32], a configuration considered optimal for the efficient execution of the work so the analysis was based on the productive performance of this team during a standard 8-hour workday over a period of 5 days. Once the total area covered during that period was determined, the quantities of materials required per m² were calculated. This calculation includes an additional percentage to account for material waste inherent to manual production processes, as detailed in Table 6.

Table 6. Waste percent

DESCRIPTION	% WASTE
Lime	3
Soil	5
Water	5

3. Results and Discussion

The technical test results of the soil–lime mixtures with lime contents of 0%, 4%, 6%, 8%, and 10% are presented below. These include Modified Proctor, unconfined compression and durability tests. The results of the economic component, consisting of the unit cost analysis, are also presented. These results were evaluated in accordance with local regulations to determine the feasibility of the study.

3.1. Soil Compaction Test

The results of the compaction test for the soil–lime mixtures with lime contents of 0%, 4%, 6%, 8%, and 10% are shown in Figures 4, 5, 6, 7 and 8, respectively, carried out in accordance with ASTM-D1557 [27].

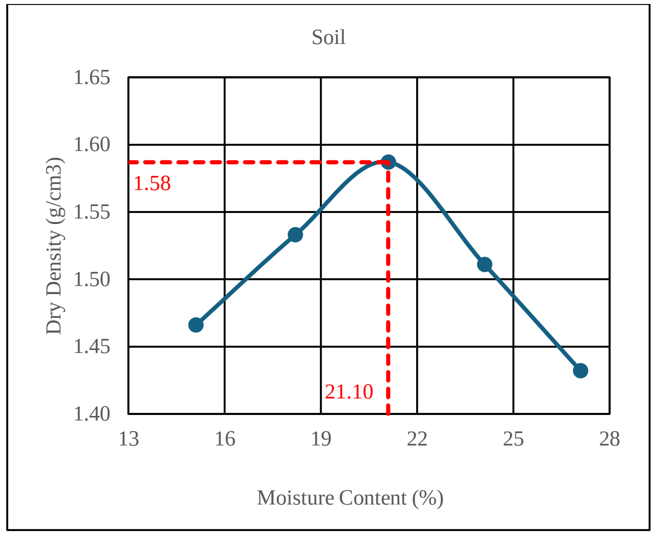

Fig. 4 Soil moisture-density curve

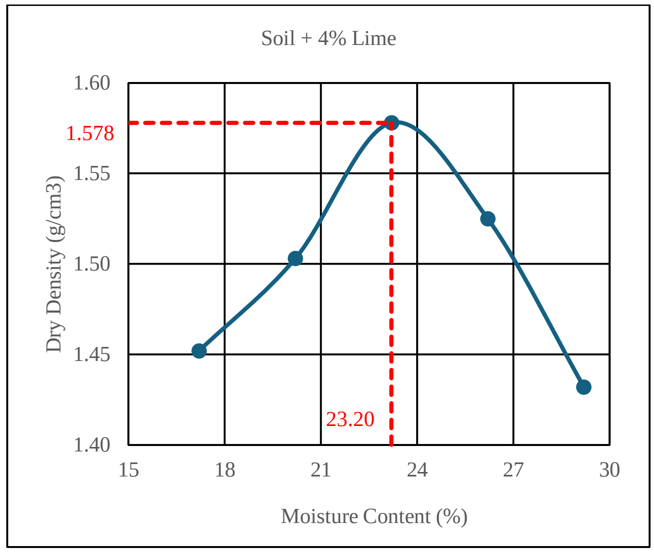

Fig. 5 Soil moisture-density curve with 4% lime

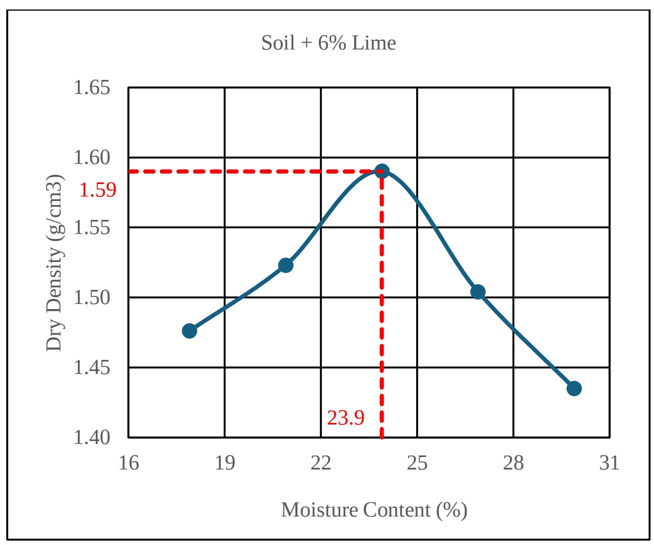

Fig. 6 Soil moisture-density curve with 6% lime

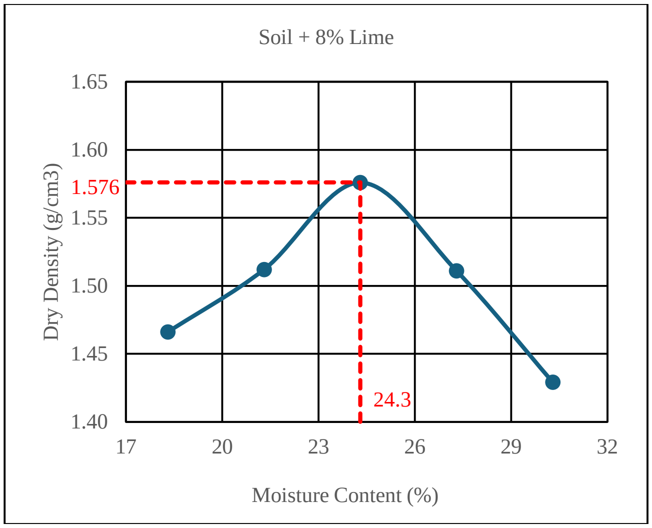

Fig. 7 Soil moisture-density curve with 8% lime

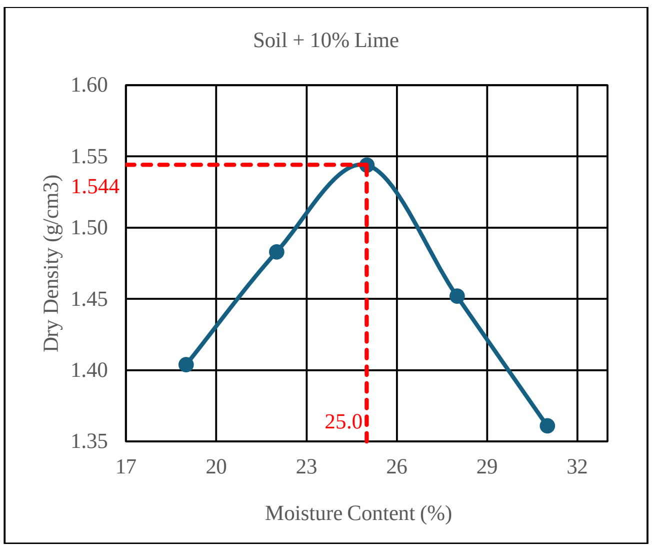

Fig. 8 Soil moisture-density curve with 10% lime

According to Table 7, the incorporation of lime increased the optimum moisture content of the material, rising from 21.1% for the natural soil to 25.0% with 10% ime, which represents an increase of 18.5%, then in contrast, the maximum dry density showed a nonlinear response, reaching a maximum value of 1.590 g/cm³ with 6% lime (+0.19% relative to the natural soil) and decreasing at higher contents, such as 10% lime, with a value of 1.544 g/cm³, representing a reduction of 2.71% and we can see that these results are consistent with the physicochemical mechanisms of lime stabilization: cation exchange and flocculation–agglomeration increase the water demand required to achieve the same compatibility [33], while replacement at higher lime contents tends to reduce densification so the compaction performance suggests an optimum close to 6% lime and however, the design lime content will be complemented by strength and durability tests, since the gains from pozzolanic reactions may require matching or slightly exceeding that dosage.

Table 7. Optimum water content and maximum dry unit weight

Specimen	Optimum Moisture (%)	ϒd max (g/cm³)
S	21.1	1.587
S-4%	23.2	1.578
S-6%	23.9	1.590
S-8%	24.3	1.576
S-10%	25.0	1.544

3.2. Unconfined Compressive Strength

Tables 8 and 9 indicate the unconfined compressive strength results after 7 and 28 days of curing. Three specimens were tested for each lime percentage, including 0%, 4%, 6%, 8% and 10%, in accordance with ASTM D2166 [28] for the natural soil and ASTM D5102 [29] for the lime-treated soil.

Table 8. Unconfined compressive strength at 7 days of curing

Specimen	0%	4%	6%	8%	10%
C-01 (kg/cm²)	10.89	11.09	12.91	12.66	9.10
C-02 (kg/cm²)	11.46	10.32	12.94	12.29	8.55
C-03 (kg/cm²)	10.65	10.81	13.51	12.58	9.08
Average	11.00	10.74	13.12	12.51	8.91
Standard Deviation	0.42	0.39	0.34	0.19	0.31
Av - SD	10.58	10.35	12.78	12.32	8.60

According to Table 8, the strength increased from 10.58 kg/cm² (0%) to a maximum of 12.78 kg/cm² (6%), and then decreased to 8.60 kg/cm² with 10% lime. The 4% lime content showed a value slightly lower than that of the natural soil, indicating that part of the lime had not yet generated sufficient pozzolanic products for its reaction. Compared with 7-day criteria, all lime contents exceeded the typical minimum of 3.52 kg/cm² for lime-treated subgrades [34], and in the case of 6% and 8% lime, they reached the threshold used for lime-treated bases, which is a minimum of 10.55 kg/cm² [35].

Table 9. Unconfined compressive strength at 28 days of curing

Specimen	0%	4%	6%	8%	10%
C-01 (kg/cm²)	14.06	18.75	22.34	21.33	17.02
C-02 (kg/cm²)	14.31	19.04	21.84	21.09	16.34
C-03 (kg/cm²)	14.53	19.69	22.60	21.99	16.98
Average	14.30	19.16	22.26	21.47	16.78
Standard Deviation	0.24	0.48	0.39	0.47	0.38
Av - SD	14.06	18.68	21.87	21.00	16.40

According to Table 9, the mixtures with 6% (21.87 kg/cm²) and 8% (21.00 kg/cm²) showed the best performance, while 10% (16.40 kg/cm²) was again the content that achieved the lowest strength. Compared with the UFC 3-250-11 guide [36] for lime-stabilized soils at 28 days, the minimum required values are 14.06 kg/cm² for subbase/subgrade under rigid pavement and 17.58 kg/cm² under flexible pavement. As a result, 6%, 8%, and 4% are acceptable for flexible pavements; however, 10% would not meet this requirement, as it only complies with the rigid pavement specifications. Additionally, the 0% compliance only meets the minimum rigid pavement specifications. The 6%-8% range represents the best design dosage, and the 4% dosage could be acceptable with moderate traffic loads.

The 28-day compressive strength data were also checked with ANOVA. The result obtained was $F = 204.46$ and $p < 0.001$, showing that the mixes did not behave equally in terms of strength. In general, this confirms that lime addition changed the mechanical performance of the stabilized soil. The 6% lime mixture tested had the highest average compressive strength (22.26 kg/cm²) and maximum dry density. Given the highest compressive strength, highest dry density, and that it meets the ASTM D559 [30] durability standard and has the lowest amount of lime used (compared to 8% and 10% mixtures), the best mix proportion for the soil being studied is the 6% lime mixture.

Dhar and Hussain [10] showed that unconfined compressive strength increases progressively when soil is stabilized with lime and allowed to cure for a longer time, and they point out that even with 3% lime at 7 days, sufficient values are obtained to improve subgrades. The same trend occurs in this study, but with higher strengths from early ages; for example, at 7 days, the 6% lime content reaches 12.78 kg/cm². This difference is supported by the fact that the type of soil and the compaction and curing conditions directly influence the magnitude of the strength achieved.

Rodríguez and Hidalgo [11] identified an optimum lime range between 6% and 9% to maximize the mechanical performance of stabilized soil. The results of this study are consistent with that finding because the best behavior is concentrated around 6% to 8%, since at 7 days the maximum value occurs at 6%, and at 28 days 8% again stands out with a very close result. However, when the lime content reaches 10%, the strength decreases, which is usually explained by an excess of lime that does not translate into more cementitious products and may also affect the densification of the mixture.

Figure 9 illustrates a comparison of the unconfined compressive strength profiles after 7 and 28 days of curing for lime contents of 0%, 4%, 6%, 8%, and 10%. The results show that the 6% lime content provides the highest strength for both curing periods.

Table 10 illustrates that adding lime increases strength for a period of 7 to 28 days, based on the natural increase in strength of the soil of 32.89% (10.58 to 14.06 kg/cm²), whereas with lime, increases in strength range from 70% to 91% for all percent lime inclusion. According to Pickering, Scullion and Estakhri [37], the typical maturity ratio (28/7) of lime-stabilized materials is considered to range from 1.5–2. This condition is satisfied by all four percentations of 4%, 6%, 8% and 10% lime in the tested materials, which supports the contribution made by the pozzolanic action of lime-clay reactions in causing increased strengths.

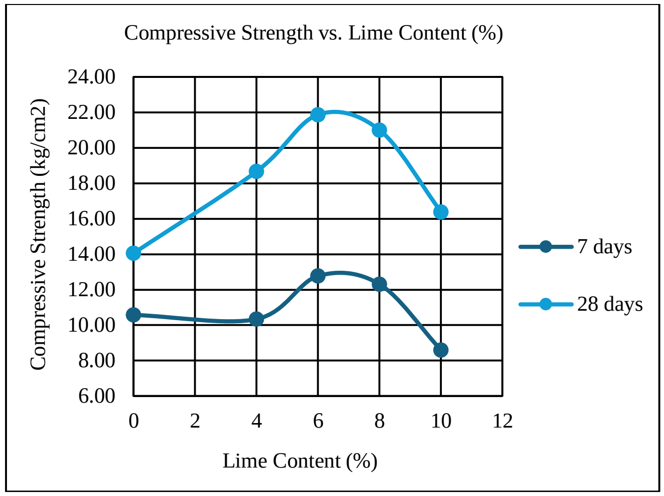

Fig. 9 Compressive strength–lime content curves at 7 and 28 days

Table 10. Strength gain (7–28 days) vs. Lime content (%)

Lime %	Strength (kg/cm²)		Gain %
	7 days	28 days	
0	10.58	14.06	32.89%
4	10.35	18.68	80.47%
6	12.78	21.87	71.13%
8	12.32	21.00	70.55%
10	8.60	16.40	90.72%

3.3. Durability Test

Table 11 shows the durability results for the soil-lime mixtures with 0% to 10% lime after 7 days of curing. The test followed ASTM D559 [30] and was used to observe how the stabilized samples behaved under repeated wetting and drying conditions.

Table 11. Durability test after 7 days of curing

Specimen		0%	4%	6%	8%	10%
Weight Loss (%)	D-01	27.39	14.65	11.51	8.42	7.58
	D-02	26.49	15.47	10.73	7.76	6.67
	D-03	27.21	14.75	11.32	8.08	6.8
Average		27.03	14.96	11.19	8.09	7.02
Standard Deviation		0.48	0.45	0.41	0.33	0.49
Avg - Sd		26.55	14.51	10.78	7.76	6.52

The average weight loss of the mixtures containing 6 to 10% lime in the wetting-drying tests was equal to or less than 14%, according to ASTM D559 [30], while the mixture containing 4% lime had a weight loss of 14.51%. With 4% lime, the average mass loss was 14.51%, but with 10% lime, it decreased to 6.52%. This shower that higher lime contents, helped the specimens resist the durability test better. As depicted in Figure 10, the treated specimens with higher amounts of lime did not lose as much weight in the wetting-drying test and had better overall durability than the untreated soil (0%), which had a weight loss of 26.55%. The lowest amount of mass loss was observed for the mixture containing 10% lime; however, any increase in lime would need to take into consideration the amount of material used compared to improving the durability of the material

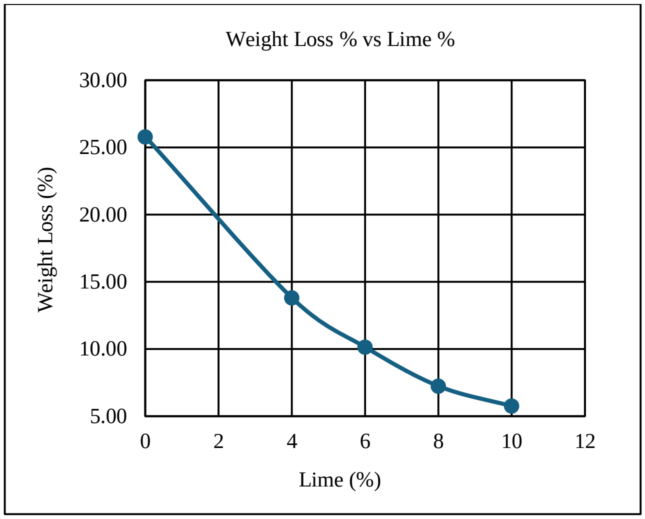

Fig. 10 Weight loss–lime content curve after wetting–drying cycles

According to statistical findings, the effect of the amount of lime on how long a mixture will last when exposed to wetting-drying cycles is significant as determined by one-way ANOVA ($F=1040.31$, $p<0.0001$). Additionally, low within-group variances mean that all mixtures had consistent and reliable experimental performance throughout the length of each mixture's respective wetting-drying cycles.

Although the 10% lime content achieved the lowest weight loss, the 6% mixture still satisfies the durability criterion while requiring less lime, which is relevant for low-cost subfloor applications. Therefore, the 6% mixture is identified as the most balanced option for subfloor applications in rural construction within the scope of this study.

3.4. Economic Analysis

Table 12 presents the productivity of two laborers during an 8-hour workday in the construction of the soil–lime subfloor layer. Performance was evaluated over a minimum period of 5 days, as recommended by, obtaining an average compaction productivity of 45.823 square meters per day.

It should be noted that this evaluation was carried out with local personnel, each equipped with the corresponding Personal Protective Equipment (PPE), under favorable weather conditions in accordance with Standard G.050 [38].

Table 12. Compaction performance of the soil-lime subfloor over 5 days

Performance	m^2/day
P-01	46.60
P-02	46.20
P-03	47.10
P-04	46.50
P-05	45.90
Average	46.46
SD	0.637
Average -SD	45.823

Table 13 shows the Unit Price Analysis corresponding to the construction of the soil-lime subfloor layer stabilized with 6% lime using the manual method. This percentage was selected as the optimum under a balanced technical- economic criterion based on the previous analyses.

The units of measurement used for the resources were: man-hour (mh) for labor, bag (bg) for lime, cubic meter (m^3) for soil and water, meter (m) for wire mesh, labor percentage (L%) for hand tools, and unit (und) for the manual tamper. In this analysis, labor cost was not considered, since the workers were local residents themselves, and the study does not have a profit-oriented approach, but rather seeks to enable the inhabitants to apply this soil–lime methodology for their own benefit.

Table 13 shows the unit price analysis for the soil-lime subfloor system, with an estimated cost of S/15.26 per square meter. This value is obtained by adding the unit prices of labor, materials, and hand tools. According to the Cost Magazine [32], the average construction price of a 3-inch concrete subfloor in the Junín Region is S/ 28.91, which represents a price increase of up to 89.45% compared with the soil–lime subfloor.

The reason for the difference in costs is because of different types of inputs. For example, the conventional system uses more expensive inputs: portland cement type IP, aggregates, and gasoline, oil, or other fuels to power machines (for example, concrete mixers and other special machinery). Therefore, the total cost for the conventional system is partially affected by the high costs of input materials. In contrast, the soil-lime system uses less expensive local materials for the base (soil, lime, and water, using simple or hand tools). So, the reported costs of the soil-lime system are reflective of a self-construction scenario where the labor will be provided by local people. If there are commercial values associated with labor, the unit price should be modified accordingly.

The quantity of ingredients needed for 1 m^2 of soil-lime was calculated using the parameters in Table 14 and the waste percentages in Table 6.

Table 13. Unit price analysis for the construction of the soil-lime subfloor

Work Item:	**Soil-lime subfloor of 3"**				**Unit Cost per m²**	**S/ 15.26**
Working Day:	**8.00 hours/day**					
Performance:	**45.82 m²/day**					
Code	**Resource Description**	**Unit**	**Quadrille**	**Quantity**	**Price (S/.)**	**Partial (S/.)**
1	**Labor**					**S/ 0.00**
1.1	Laborer	mh	2	0.349	S/ 0.00	S/ 0.00
2	**Materials**					**S/ 5.27**
2.1	Lime	bg		0.295	S/ 17.90	S/ 5.27
2.2	Water	m³		0.021	S/ 0.00	S/ 0.00
	Soil	m³		0.038	S/ 0.00	S/ 0.00
3	**Equipment and Tools**					**S/ 9.98**
3.1	Hand Tamper	mhr	2	0.349	S/ 23.00	S/ 8.03
3.2	Metal Mesh #4	m	1	0.175	S/ 9.90	S/ 1.73
3.3	Minor Tools	L %		0.030	S/ 7.46	S/ 0.22

Table 14. Specifications for the construction of the soil-lime subfloor

Thickness	3 in.
Lime Dosage	6%
Moisture content	23.90%
γ Soil–lime	1590 kg/m³
γ Water	1000 m³

4. Conclusion

Lime-stabilized soil is being used as a subfloor material in rural homes within the Chilca District. Based on testing and analysis of both economics and engineering, it is determined that this material provides an economically and technically acceptable alternative based on soil and construction conditions tested. Testing results show a positive trend (technical and economic) for mixed soils containing 4%, 6%, 8%, and 10% lime, with all tested proportions exhibiting improvements over an unaltered control sample. Through analysis of all tests conducted during this study, it was determined that the most efficient lime content to provide a balance of structural integrity was 6%, generating the highest compaction and strength results while meeting the durability test requirements.

In the compaction test, a maximum density of 1.59 g/cm³ and a maximum moisture content of 23.9% were achieved. Likewise, in the unconfined compression test, strengths of 12.78 kg/cm² at 7 days and 21.87 kg/cm² at 28 days were recorded. These values represent an increase of 20.68% and 55.55%, respectively, compared with the untreated control sample. On the other hand, the results of the durability test indicate that, as the lime content increases, weight loss decreases, complying with the international standard that establishes a maximum weight loss of 14%. In particular, with a lime content of 10%, the weight loss was 6.52%, while with 6% lime, a value of 10.78% was obtained, confirming the suitability of this material for implementation in construction. For these reasons, the implementation of this material with a 6% lime content is proposed, since it is the lowest dosage that provides high and suitable results across the three technical tests carried out in the research.

The Economic Analysis shows that the soil–lime material represents a cost-effective alternative under the self-construction scenario evaluated, with a cost of S/ 15.26 per m², which means a savings of 47.23% compared with conventional plain concrete budgets in the region. This economic advantage makes it a feasible solution for communities with limited resources. For these reasons, its implementation is recommended for the housing of low-income families, since it combines easy access to materials, with lime being the only externally sourced input, with adequate technical properties and a reduced cost under the assumptions of this study. To ensure the performance and durability of the material, it is essential to provide basic training in its application, as well as to ensure proper surface cleaning of the area and adequate hydration during the placement process.

The study performed a standardized lab evaluation of the durability performance of soil/lime mixtures per ASTM D559 [30]. Long-term monitoring of the field was not included in this study, and it is recommended that future studies conduct long-term assessment of the behavior of stabilized subfloors under actual service conditions in rural housing sites, in order to verify lab findings and evaluate for extended service life. Also, this study provides information that is specific to the soil and environmental conditions in the study area, which is located in the Junín region of Peru. It is therefore suggested that extrapolating the optimum dosage of lime proposed in this study to other regions or types of soil, having dissimilar geotechnical characteristics or mineral composition, must be done with caution. Due to possible variability in soil characteristics, additional validation will need to be performed under a variety of regional conditions prior to implementing this method in a greater number of locations.

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